Review on seaport and airport adaptation to climate change: a case on sea level rise and flooding

Mark Ching-Pong Poo[1], Zaili Yang[1*], Delia Dimitriu[2], Zhuohua Qu[3]

1. *Liverpool Logistics, Offshore and Marine Research Institute, Liverpool John Moores University, UK*
2. *Centre for Aviation, Transport, and the Environment, Manchester Metropolitan University, UK*
3. *Liverpool Business School, Liverpool John Moores University, UK*

Abstract

Seaports and airports are the critical nodes of international supply chains and thus stand on the edge of social and economic disasters. They are often affected by extreme and rough weather. Comparing all climate threats, sea level rise (SLR) and storming and flooding currently present, according to the relevant literature, the most severe impact in ports and airports. This paper aims to provide a comprehensive review of seaport and airport adaptation to climate change with a focus on SLR and flooding. We have summarized all related research papers and divided them into different types and described the trend of studies. After that, the study involves a comparison to analyse the synergy between previous studies in seaports and airports, and provides insights for the further studies to emphasise the needs and opportunities

[*] Corresponding author: z.yang@ljmu.ac.uk

for the collaborative work that can complement the adaptation planning of and ensure the resilience of seaports and airports.

Keywords: climate change, climate impact assessment, vulnerability assessment, risk assessment; cost-benefit analysis, climate adaptation, transportation resilience;

1. Introduction

Over the past few years, the focus on climate change studies has switched from mitigation to both mitigation and adaptation. As the global warming brings more extreme weather, the accidents and failures become more frequent and the losses and fatalities are more severe. In the past two decades, several serious weather-related events are causing significant economic loss and deaths. In 2005, Hurricane Katrina in the United States was one of the deadliest hurricanes (CNN Library, 2017). In 2011, Tohoku Japan Tsunami destroyed several provinces (CNN Library, 2017). It brought more than 15,000 death, and about 230,000 people lost their homes. In 2011, Missouri experienced the deadliest U.S. tornadoes, which killed 161 people (Wheatley, 2013). In 2012, Louisiana Mississippi, Alabama and Arkansas had faced a strong and rainy Hurricane Issac, which caused $2.0 billion in terms of insured loss and left more than 644,000 people without power (Castellano, et al., 2012). In 2013, a two mile-tornado near Oklahoma City caused more than 50 death and destroyed many homes (Howell, et al., 2013). During 2017 Atlantic hurricane season, there are more than 9 hurricanes threatening North America and Caribbean areas. Until October, hurricanes, including the most powerful Maria, brought more than 200 billion lost and 103 death toll in the U.S. (Johnson, 2017). Transportation is highly affected by extreme weather,

especially by flooding and storming. Seaports and airports are the critical nodes of international supply chains and thus stand on the edge of social and economic disasters. It is therefore important to review the previous studies and understand the research gaps for future research directions.

In the previous years, there were some literature reviews in similar research areas. However, they did not focus on seaports, airports, against SLR and flooding. For examples, Jonkeren and Rietveld did any other review for waterborne transport infrastructures with an economical focus (Jonkeren & Rietveld, 2016) and Lee did a review with a focus on emission reduction for all transport mode (Lee, 2007). given the similarity of seaports and airports, it is valuable and beneficial to conduct a comparative analysis on their climate adaptation measures for cross fertilisation.

2. Methodology of literature review

To carry out a comprehensive literature review of seaport and airport adaptation to climate change, we have set up a systematic analysis for articles searching and selection. With reference to Wan (Wan, et al., 2017) and Luo (Luo & Shin, 2016), we can divide the whole data collection process in three steps:

1. Online database searching;
2. Article screening;
3. Final refining and analysing.

Firstly, we collected papers on climate change adaptation of seaports and airports with a focus on flooding and storming from all of the peer-reviewed academic journals on Web of Science (All Database). It is one of the most comprehensive multidisciplinary searching platforms for academic research (Hosseini, et al., 2016; Luo & Shin, 2016; Wan, et al., 2017). We used different strings, such as the combination of the elements from the sets of (flooding or flood or adapt or adaptation or resilience), (airport or seaport or port), (flooding or flood), (resilience or adapt or adaptation), and (airport or seaport or port)", as 'Topic' items to perform the searching process. Throughout the searching process, we have used 'OR' function to finish the journals collection. The search was completed in October, 2017, covering the period from 1970 to 2017. 501 relevant papers were collected.

Secondly, we conducted a two-stage screening process to secure the relevance and quality of the selected articles. In the first stage, we sorted out the peer-reviewed journals and eliminated the book chapters, conference proceedings, editorial materials and non-peer-reviewed journals. The peer-reviewed journal papers were chosen for analysis because it is the most guaranteed type of documents for the acceptance of the scientific community (Bergström, et al., 2015). We reduced the number of articles from 501 to 383. In the second stage, we studied titles, keywords, and abstracts of the chosen 383 articles to confirm their relevance. For example, some articles related to ecosystem (Hirst, et al., 2016) and other climate change impacts (Y.Tham, et al., 2011), which are irrelevant to flooding and storming, were eliminated. After the second screening, the number of the selected articles was reduced to 105.

Finally, we carefully conducted the full-text review for the refined 105 articles. As a result, the articles that have no focus on flooding and storming impact on transportation, are also eliminated. After the final refining process, 88 articles remained. We analysed the articles by the distribution of their publishing years, authors, journals, regions, transportation modes and research methods. We found that the research interests and the corresponding trends of different research themes. Furthermore, we analysed the connection of leading authors through their collaborative papers. Finally, we compared the studies on seaports and airports to guide the directions of further studies.

3. Analysis of studies

3.1. Trend of studies

The refined 88 journal articles are distributed from 1985 to 2017 and represented in Figure 1. The earliest refined journal is from 1985. 2012, 2015 and 2016 are the years with the highest number of journal articles, such as 12, 16 and 17 respectively. The number of corresponding papers is increasing rapidly. In the period of 2008 - 2012, the number of articles is four times more than that of 2003-2007, while in the period of 2013-2017, the number of articles doubles compared to that of 2008-2012 and is more than the total before 2013. Such a growth clearly indicates the importance and urgency of the research topic and well reflects the fact that climate change involving both mitigation and adaptation is of high priority at both national and international research agenda. It is foreseen that there will be more studies and relevant outcomes and publications in this field in the next decade given the increasing effect of climate change to transportation and our social welfare.

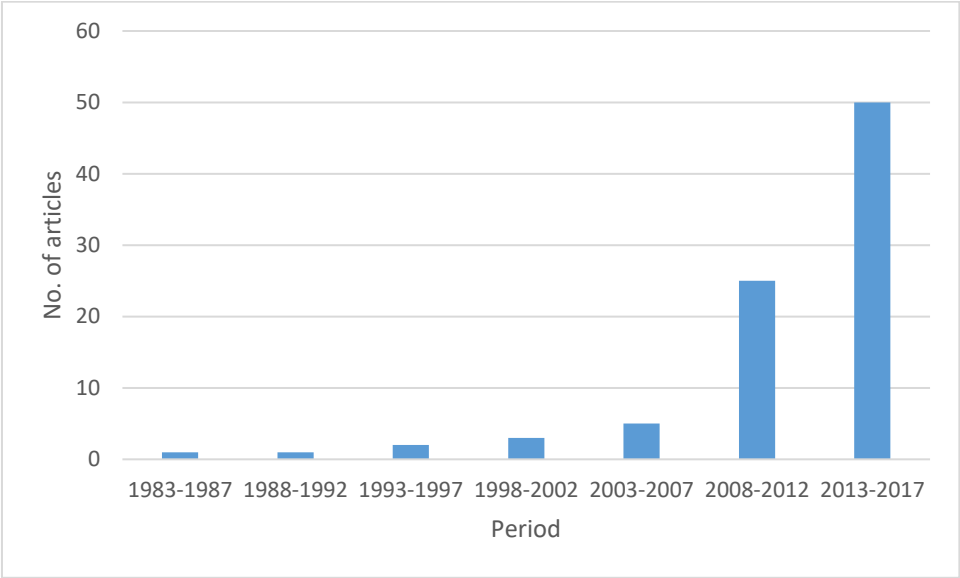

Figure 1 Distribution by publishing year

3.2. Distribution by journals

After assessing the trend of studies, we need to assess the articles by the prospect of journals. We list the top journals, which means more than 2 articles, in Table 1. Among all articles, Climatic Change is the most contributed journal as it published 6 journal articles that were related to the topic. Other leading journals include Journal of Coastal Research, Natural Hazards, Coastal Engineering Journal, Journal of Geophysical Research, Ocean and Coastal Management, Ocean Engineering, Regional Environmental Change, Revista de Gestão Costeira Integrada, Sustainability Science. If the journals are with the same number of articles, we list them out by alphabetic order in the journal list. It is clearly seen that the topic has diversified features and attracts attention and interest from a wider audience from costal research, geographical science, ocean engineering and environmental and sustainability studies.

Table 1 Top 10 journals

No.	Journal Title	No. of articles
1	Climatic Change	6
2	Journal of Coastal Research	4
3	Natural Hazards	4
4	Coastal Engineering Journal	2
5	Journal of Geophysical Research	2
6	Ocean and Coastal Management	2
7	Ocean Engineering	2
8	Regional Environmental Change	2
9	Revista de Gestão Costeira Integrada	2
10	Sustainability Science	2

3.3. Distribution by authors

This section evaluates the distribution of the leading authors. Table 2 shows the top authors. Among all articles, Austin Becker and Robert Nicholls are the most contributed scholars in the field. There are also 15 more authors contributing more than 2 articles. Analysing their afflictions could also help us to identify the strong research groups/labs in the world in the investigated area. Statistical analysis on the papers of multiple authors from different research groups indicates that so far there are no significant critical mass being formed from the listed leading authors, which reveals that the studies in the field are being carried out rather individually and the issues are being tackled from different perspectives based on the expertise possessed by different groups. Therefore, it shows a good potential to integrate the

complementary expertise from the leading authors to match the diversified features of climate adaptation research, involving hazard analysis, impact assessment, risk modelling, resilience engineering, geographical studies and environmental and sustainability science. .

Table 2 Top 17 authors

No.	Author Name	No. of articles
1	Becker, Austin	4
2	Nicholls, Robert	4
3	Corfee-Morlot, Jan	3
4	Fischer, Martin	3
5	Hallegatte, Stéphane	3
6	Chhetri, Prem	2
7	El-Raey, Mohamed	2
8	Esteban, Miguel	2
9	Frihy, Omran El Sayed	2
10	Gekara, Victor Ovaro	2
11	Hanson, Susan	2
12	Herweijer, Celine	2
13	Ng, Adolf K.Y.	2
14	Nursey-Bray, Melissa	2
15	Pugh, D.T.	2
16	Ranger, Nicola	2
17	Schwegler, Ben	2

3.4. Distribution by regions

Apart from assessing the authorship of the journal articles, we investigate the regions of studies through the analysis of the authors' affiliations. We evaluate the regions by the locations of the first authors' institutions, and the result is shown in Figure 2. Europe occupies 32%, involving 28 articles. It is followed by North America, Africa, Asia, Oceania, Latin America and the Caribbean. In general, European and American academic institutions (counting 49% of the total) remain a world leading position in climate change adaptation with a focus on flooding and storming. It provides the useful insights as to where the possible best practices and solutions to storming and flooding in seaports and airports are located in the world nowadays.

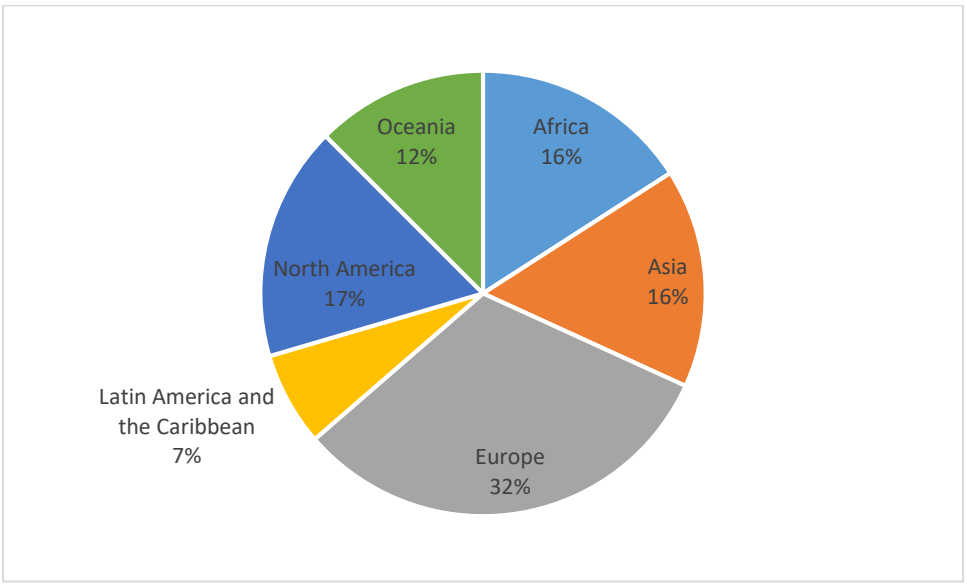

Figure 2 Distribution by regions

3.5. Distribution by transportation modes

In this section, we analyse the difference between the relevant studies in seaports and airports. By reviewing all the 88 papers, we carry out the analysis by separating them into three groups, seaports, airports and combi. It is because some regional coastal assessments have not stated that they are unique for any transportation mode (e.g. airports or seaports), instead they tackle large regions involving both seaports and airports. The result is shown in Figure 3. “Combi” has the largest ratio of 57%, involving 50 articles. “Seaport” and “Airport” have 39% and 4% respectively. It reveals two important information that can trigger some interesting future studies. One is that within the context of adaptation to flooding and storming, there are high synergies between airports and seaports given that 57% of the investigated papers treat them together. The other is that seaports attract more research attention in the area. Research on the difference and similarity between airport and seaport adaptation planning to flooding and storming is demanded and the comparative analysis between them also needs to be conducted to find the reason why adaptation research in airports is less than that in seaports. Furthermore, there is a vast difference between it in terms of research topics Airports have more research focuses on operation and climate risk assessment, while seaports are associated with other research topics as indicated in Figure 4. Research topics are detailed in Section 3.8.

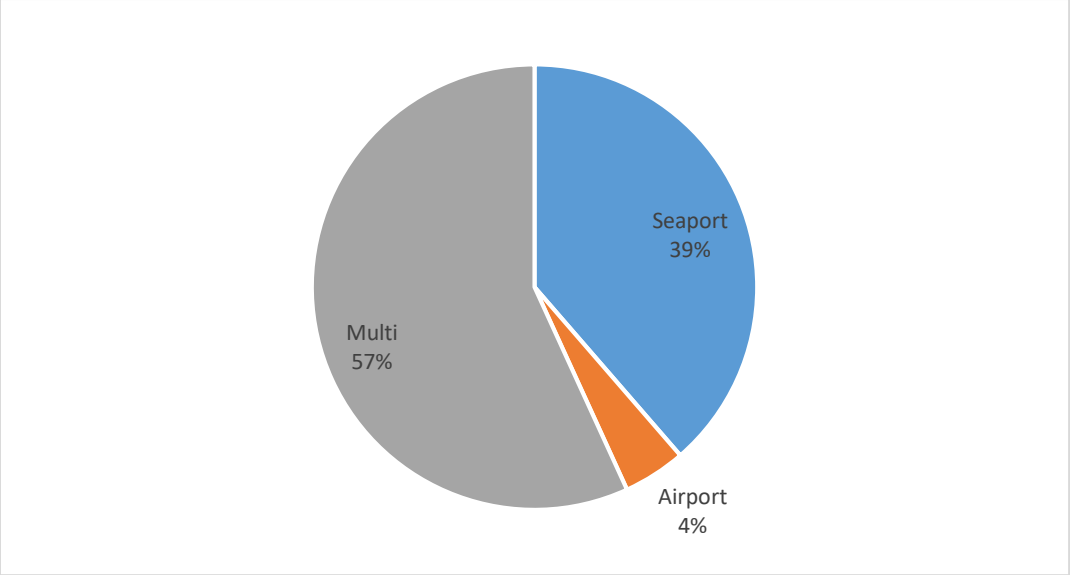

Figure 3 Distribution by transportation modes

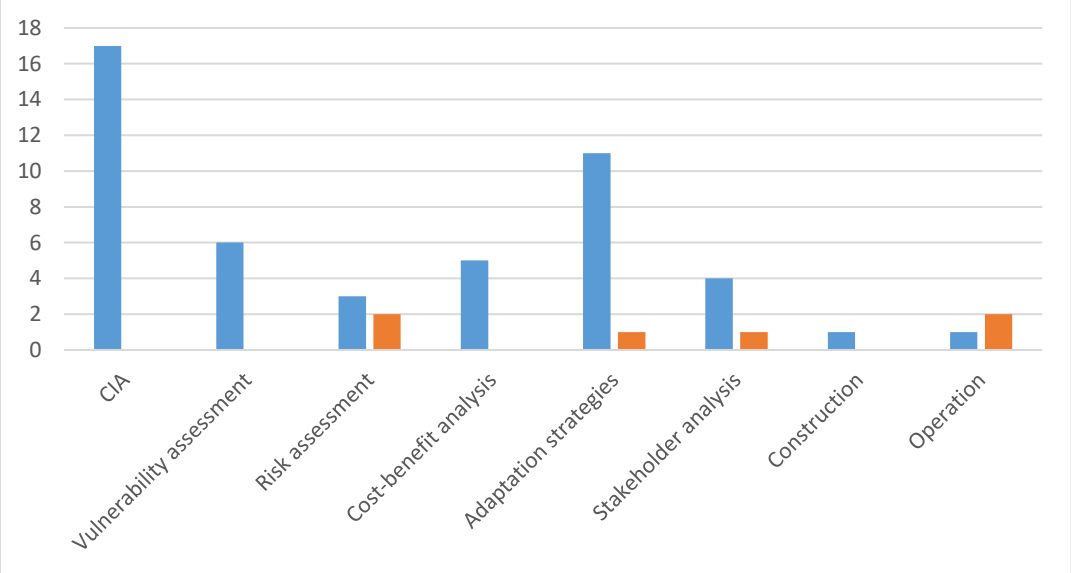

Figure 4 Distribution by research interests with split of airports and seaports

3.6. Distribution by research types

We conducted the simple division between quantitative research and qualitative research by their basic characteristics. Quantitative research considers hard science which consists of statistical analyses (Mugenda & Mugenda, 1999). On the other hand, qualitative research considers soft science which words are more important

throughout the whole research. The result is shown in Figure 5. Quantitative research takes an important role in these kinds of studies as it got 59 articles and 67% in total. The remaining is qualitative research, which consisted of 29 articles and 33% in total. The main quantitative methods used include simulation and mathematical modelling. A simulation method is used to study the operation of a real-world or a theoretical process/system under various pre-set circumstances for different purposes (e.g. numerical testing, observing behaviour, optimising performance, or exploration of new states). Mathematical modelling refers to those applying mathematical concepts and languages to describe and represent objective reality. The qualitative methods are conceptual work and case studies. The conceptual work includes analysis on concept issues such as definitions, properties, theoretical framework and conceptual modelling. A case study refers to an in-depth examination of a particular person, community or situation, which usually can be achieved via interviews. By reviewing the 88 papers, it is also found that lack of data is a common problem discussed in both qualitative and quantitative studies. Therefore, how to address the unavailability and uncertainty in data to support rational decision in this area remains unclear, wanting solutions from future studies to be found.

Figure 5 Distribution by research types

3.7. Distribution of research methods

Following the analysis in Section 3.6, this section analyses the detailed research methods in the 88 papers, including:

- Review
- Survey
- Framework
- Modelling
- Simulation

The studies that involve more than one method are counted multiple times. The result is shown in Figure 6. The most common method is “Modelling” representing 39 articles in total. The second and third most common methods are “Framework” and

"Review", where the numbers of articles are 32 and 29 respectively. "Simulation" and "Review" are at the bottom, relating to 10 and 4 papers, respectively.

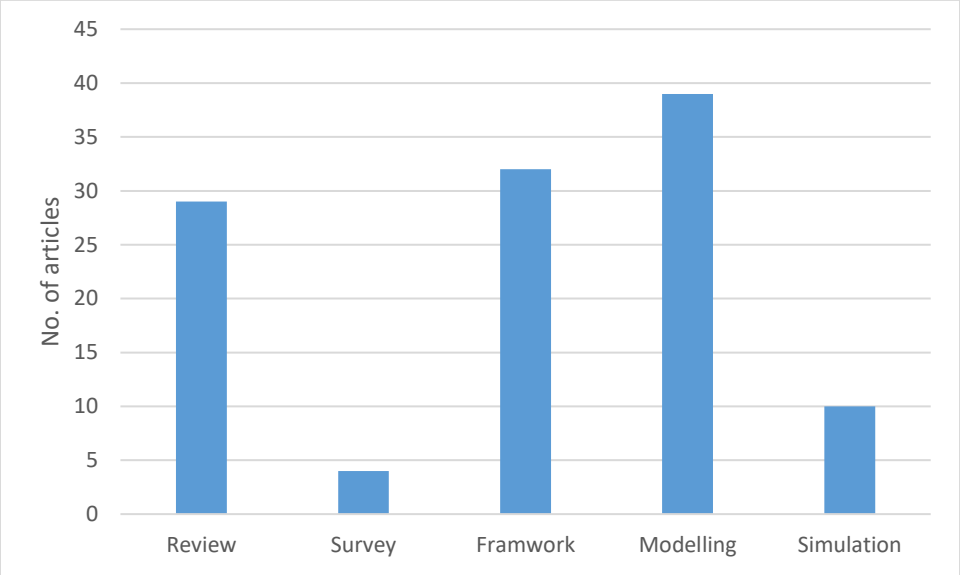

Figure 6 Distribution by research methods

3.8. Distribution of research topics

In terms of research topics, we have identified several different types:

- Climate impact assessment (CIA)
- Vulnerability assessment
- Risk assessment
- Adaptive strategies
- Cost-benefit analysis
- Stakeholder analysis
- Construction
- Operation

The definitions of CIA, vulnerability assessment and adaptive strategies are in line with those from IPCC report (IPCC, 2014). The report presents a fundamental adaptation planning framework containing such important concepts. CIA is a study describing the trend of climate change, where the impacts can be rising temperatures, sea level rise (SLR) and others. A vulnerability assessment for climate change is the process of identifying and quantifying the vulnerabilities in a specific region or infrastructure. Adaptation strategies mean the case study of local and regional transportation infrastructure by introducing the adaptive management of a particular region or transportation system. Besides, risk assessment requires the combination of study in threat, vulnerability and impact factors (Liu, et al., 2012). Cost-benefit analysis based on the economic analysis of a system or infrastructure adaptation strategies means the case study of local and regional transportation infrastructure by introducing the adaptive management of a particular region or transportation system. Stakeholder analysis is a methodology to facilitate institutional and policy reforming processes by accounting and often incorporating the needs of those who have an interest in the reforming under consideration (World Bank Group, 2001). Construction and operation mean the studies, not in the adaptation planning process but the post-planning process. Some investigated papers contain more than one topic, and hence are counted multiple times in the statistics in Figure 7.

The result is shown in Figure 6. The most common research method is “CIA” and there are 44 articles in the group. It is followed by adaptation strategies, vulnerability assessment, cost-benefit analysis, risk assessment, stakeholder analysis, operation, construction. Obviously, studies in the adaptation planning process is far more than

those in the post-planning stage, and dominate the research on seaports and airports adaptation to flooding and storming. It indicates the current construction and operations of airports and seaports have not yet taken into account climate adaptation significantly. Adaptation strategies are made largely based on CIA, receiving more and more support from vulnerability assessment, risk assessment and cost benefit analysis, to make the climate adaptation research in seaports and airports more systematically. Furthermore, stakeholder analysis shows a huge potential to grow in the next decade when more adaptation strategies are developed, requiring the balancing of different interests of multiple stakeholders for their implementation.

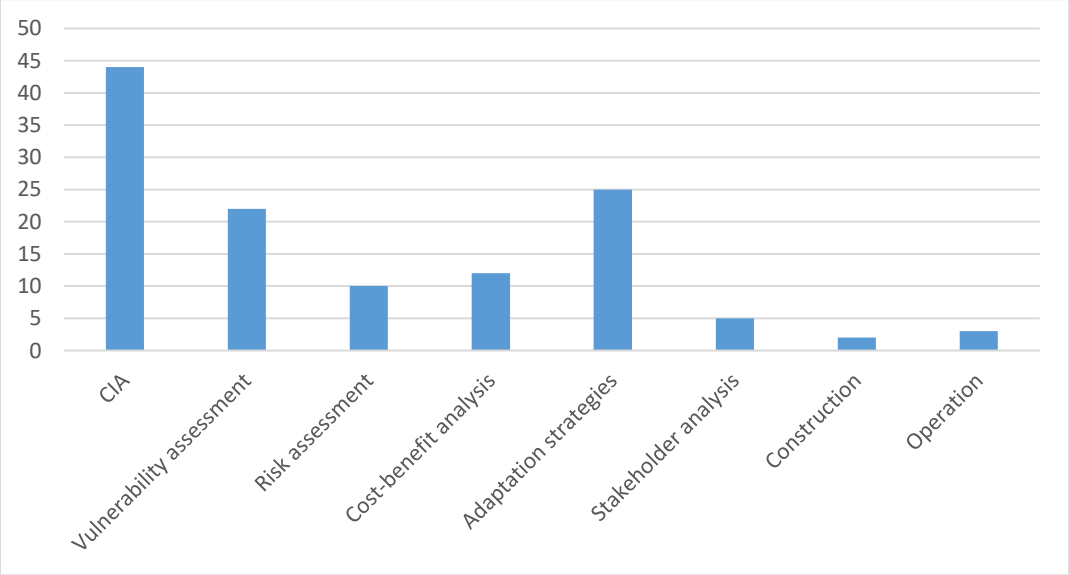

Figure 7 Distribution by research interests

4. Evolution of the studies

Due to the complexity of studies, the evolution of the studies is discussed from 8 perspectives with respect to the 8 topics in Section 3.8. The directions of the research

are researched in a chronological order of the 8 topics one by one after the comparison of the publication year of the first paper of each topic in Table 3.

Table 3 The earliest years for different research interests

CIA	Vulnerability assessment	Risk assessment	Cost-benefit analysis	Adaptation strategies	Stakeholder analysis	Construction	Operation
1985	1997	2008	2013	2008	2013	2016	2015

4.1. Evolution of CIA

In 1985, Prasad and Reddy started to assess the sea level fluctuation monthly and annually in India and recorded in academic journals in the first time (Prasad & Reddy, 1985). In 1991, apart from sea level rise, Gornitz had designed coastal vulnerability index (CVI) to raise high-risk coastal segments with a case study in the U.S. (Gornitz, 1991). A few years later, Dhaw and Forbes expanded the range of CIA from SLR to flooding and storming (Dhaw & Forbes, 1995). In 1999, Hubbert and McInnes designed a storm surge inundation model for coastal planning in Australia (Hubbert & McInnes, 1999). In 2000, Pirazzoli made a flooding statistical probability study on the Atlantic coast of France (Pirazzoli, 2000). In 2003, Hunter made a tailor-made SLR assessment for seaports in Tasmania (Hunter, et al., 2003). In 2009, CIA was integrated with GIS for assessing digital elevation model (DEM) to make an Integrated Coastal Zone Management Plan by Snoussi (Snoussi, et al., 2009). In other words, scholars started to combine CIA with vulnerability assessment by GIS spatial analysis. In 2010, Frihy contributed to the evolution by upgrading the SLR assessment from recording to forecasting its values in different scenarios (Frihy, et al., 2010). In 2015,

Becker combined CIA with vulnerability assessment and adaptation strategies from a whole climate adaptation planning perspective (Becker, et al., 2015). In 2017, there are two special assessments for seaports. One is for harbour operability (Sierra, et al., 2017) and one is for studying extreme wind events (Repetto, et al., 2017).

4.2. Evolution of vulnerability assessment

In the late 90s, El-Raey team undertook two vulnerability assessments of the coastal zone of Egypt, Nile Delta and Port Said Governorate (El-Raey, 1997; El-Raey, et al., 1999). They used remote sensing for GIS spatial analysis. After a decade, studies on vulnerability assessment arrived at a new stage. In 2008, Sterr integrated vulnerability assessment with adaptation strategies by clustering the assessment into a smaller region (Sterr, 2008). At the same time, GIS spatial analysis by DEM began to be widely used in vulnerability assessment (Gravelle & Mimura, 2008; Snoussi, et al., 2009). In 2015, Akukwe and Ogbodo connected the studies of vulnerability assessment to emergency planning for setting up vulnerability indices and ranking these indices across the 13 costal zones they investigated (Akukwe & Ogbodo, 2015). At the same time, Musekiwa et al. set up a risk analysis table from vulnerability assessment to connect risks and vulnerabilities (Musekiwa, et al., 2015). In 2016, Zanetti et al. proposed Climate Change Vulnerability Index (CCVI) with a case study in Brazil (Zanetti, et al., 2016).

4.3. Evolution of risk assessment

In 2008, Reid established a framework of climate risk analysis of seaports (Reid, 2008). In 2010, Briguglio connected risk assessment with adaptation suggestions (Briguglio, 2010). In 2012, Keokhumcheng et al. assessed the flood risk in airports. Bangkok Suvarnahumi Airport was used for the case study. In 2015, risk assessment became more systemic by linking to vulnerability assessment (Musekiwa, et al., 2015). Furthermore, Yang et al. developed a new risk analysis model in 2017 for climate risk quantification in a situation where objective data relating to risk parameters are not available (Yang, et al., 2017).

4.4. Evolution of cost-benefit analysis

In 2013, Nicholls et al. summarized the coastal planning experience from England and Wales. They started to include cost estimation. After that, there was vulnerability assessment including cost estimation (Musekiwa, et al., 2015). Genovese and Green began to predict the damage of storm surge by modelling methods in 2015 (Genovese & Green, 2015) and Hoshino commenced to estimate and compare the loss caused by future storm surges with and without adaptation strategies in the Greater Tokyo area (Hoshino, et al., 2016). Cost-benefit analysis was formally integrated into the rational development of adaptation measures.

4.5. Evolution of adaptation strategies

The earliest article clearly presenting the climate change adaptation element in seaports and/or airports was published in 2008 (Sterr, 2008). Afterwards, many articles with adaptation measures and/or strategies were published (Briguglio, 2010;

Becker, et al., 2015; Hoshino, et al., 2016). Between 2012 and 2013, there were several review papers published to address the use of adaptive measures. Osthorst and Mänz provided a preliminary typology of forms of sectoral adaptation to climate change by literature reviews (Osthorst & Mänz, 2012). At the same time, Wilby and Keenan identified evidence of different types of adjustment by follwoing the flooding in Victoria, Australia (Wilby & Keenan, 2012). One year later, Becker et al. addressed a note for seaports on climate change adaptation. Furthermore, they discussed the needs and contributions of stakeholders of seaports (Becker, et al., 2013). In 2016, Mutombo and Olcer developed a three-tier (Policy-Management-Technology) framework for seaport Infrastructure adaptation. At the same year, Burbidge stated a climate adaptation review on EUROCONTROL for European airports (Burbidge, 2016). In 2017, Becker used boundary objects, different adaptation scenarios, to stimulate ideas of storming resilience for seaports (Becker, 2017).

4.6. Evolution of stakeholder analysis

After developing adaptation strategies for several years since 2008, Becker et al, and Peirson et al. stated the importance of stakeholders' participation in the whole adaptation planning for seaports in 2013 (Becker, et al., 2013) and especially for estuaries in 2015 (Peirson, et al., 2015) respectively. Moreover, Burbidge recorded the consultation of European aviation stakeholders in climate change adaptation for airports in 2016. In 2014, Nursey-Bray studied how the port governance on negotiating climate adaptive management for facilitating regional, national and transnational networks and governance flows (Nursey-Bray, 2014).

4.7. Evolution of construction

In terms of the construction in the post planning process, the previous articles focused on new construction methods as one of adaptation measures. In 2016, Becker et al. developed a way to estimate climate sensitive construction materials applied to seaport protection (Becker, et al., 2016). At the same year, Chow et al. designed a new coastal structural concept for climate change adaptation in Hong Kong and undertook a relevant cost-benefit analysis (Chow, et al., 2016).

4.8. Evolution of operation

As far as seaport and airport operations for climate adaptation, previous articles focused on extreme weather operations. In 2015, Herath et al. integrated spatial and temporal downscaling approaches to develop an intensity–duration–frequency (IDF) model for assessing sub-daily rainfall extremes for the Perth airport area (Herath, et al., 2015). In 2016, Chhetri et al. used Container Terminal Operations Simulator (CTOS) to simulate extreme weather event impacts on port operation (Chhetri, et al., 2016). At the same year, Dun and Wilkinson invented a network graph approach to increase the resilience of air traffic networks (Dunn & Wilkinson, 2016).

4.9. Comparison of airport and seaport climate adaptation studies

For comparing the airports and seaports, all “combi” articles are eliminated to ease the comparison. There were 38 articles in total. The distribution of transportation mode is

shown in Figure 7. There were more contributions in seaports than those in airports. Seaports got 89% with 34 articles and airports just got 11% with 4 articles.

5. Conclusion

This review paper discloses and allows the scholars in the relevant areas to access the information on the trend and the characteristics of studies on seaport and airport adaptation to climate change with a particular focus on sea level rise and flooding. It describes the evolution of the studies of different research topics and shows the gaps for future research agenda along with the statistical analysis with respect to different criteria.

The studies of related topics developed rapidly in the previous decade. The research interests have been expanded from CIA, vulnerability assessment and risk assessment to adaptation strategies and the other specific studies, including cost-benefit analysis, construction and operation. We can foresee that there will be more studies in more specific topics. Except the mentioned categories, land use planning (Morel, et al., 2013) and management issues (Jasmine Siu Lee, et al., 2013; Burbidge, 2016) can be the new areas of specific studies. Also, storming and wind impacts have not been assessed comprehensively due to the complexity of the wind forecasting. So, this area also has a great potential for further analysis.

Compared to seaports, airports attract fewer/no studies on some research topics within the context of their adaptation to flooding and storming. Obviously, there is a high demand for the relevant studies to be carried out to ensure the climate resilience

of airports, probably by referencing the studies undertaken in seaports given their similarity and synergy. Furthermore, more seaports studies in the post planning operations are expected. From the evolution analysis of each research topic, the established solutions to date have so far been largely piecemeal at the level of individual research topics, despite the fact that more and more studies start to combine multiple topics together. Integrating all the research topics, from both planning and post-planning perspective for an integrated climate adaptation framework is highly desirable but requires the support of creating new models and methods in each topic and a holistic mechanism to combine the supporting models and methods in a systematic manner.

Another relevant emerging research area is the connection between climate adaptation and emergency management, which was initiated by Akukwe and Ogbodo in 2015. Well established research in emergency management and relief logistic (Mostafavi & Inman, 2016; Hong, et al., 2015; Hong, et al., 2013; Meng, et al., 2017; Bozorgi-Amiri, et al., 2013) can be combined with the risk based climate adaptation planning to enhance the resilience of seaports and airport individually or in a combined way.

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